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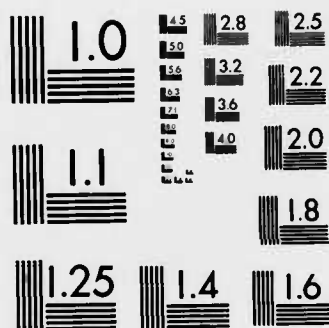
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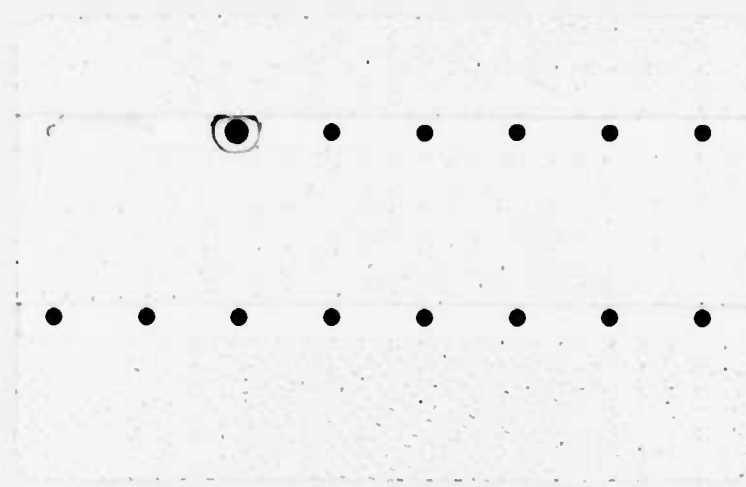




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A REDUCED GRAVITY NUMERICAL MODEL OF
CIRCULATION IN THE ALBORAN SEA

J206-81-022/6195

FINAL REPORT

Ruth Preller



Prepared For

Naval Ocean Research and Development Activity
NSTL Station, MS 39529

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A REDUCED GRAVITY NUMERICAL MODEL OF
CIRCULATION IN THE ALBORAN SEA

ABSTRACT

Oceanographic observations have shown the existence of a large anticyclonic gyre in the western Alboran Sea. Satellite imagery demonstrates the persistence of the Alboran Gyre and suggests that the direction of inflow through the Strait of Gibraltar plays an important role in determining the size and location of the gyre. Satellite data also reveals more time varying, smaller scale circulation patterns in the eastern Alboran Sea.

The reduced gravity model of Hurlburt and Thompson (1980, J. Phys. Oceanogr. 10: 1611-1651) has been adapted to the semi-enclosed basin of the Alboran Sea. The model domain is a rectangle 600 km east-west by 160 km north-south. The Strait of Gibraltar is modeled by a port in the western boundary and the eastern boundary is entirely open. When the model is forced by a northeastward inflow through the port in the western boundary, it evolves to a steady state which exhibits a meandering eastward current. The first meander of this current forms the northern boundary of a strong anticyclonic gyre in the western part of the basin. The dimensions and location of the model gyre are consistent with the persistent gyre observed to dominate the western Alboran Sea. A weaker cyclonic circulation in the eastern Alboran is also predicted by the model. This model solution closely resembles the observational data of Lanoix (1974, NATO Tech. Report 66, Brussels). The solution was obtained without including bottom topography, coastline features, or winds which have been suggested as important factors in determining the size and location of the Alboran Gyre. A preliminary investigation using the model indicates the importance of inflow angle, inflow vorticity, and the location of the Strait of Gibraltar. This model does not account for the variability observed in the circulation of the eastern Alboran Sea.

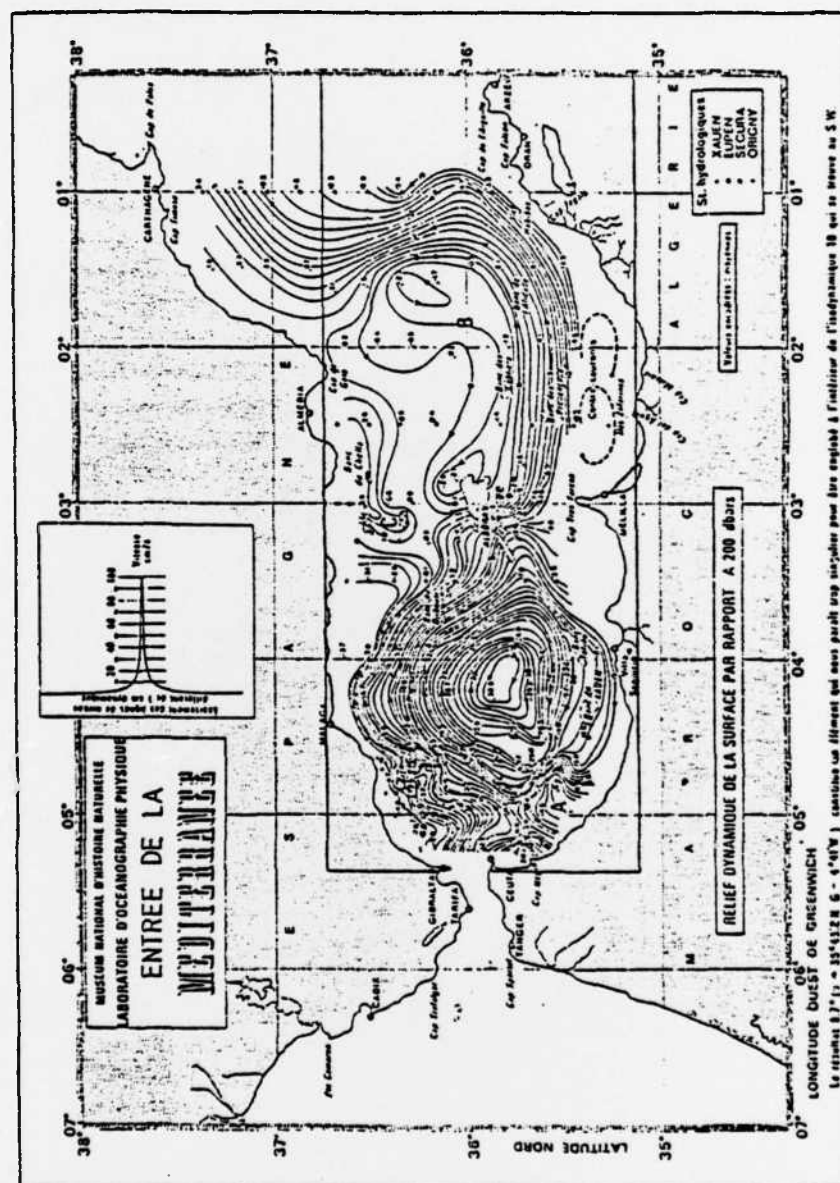
1. INTRODUCTION

The Alboran Sea is an attractive semi-enclosed domain for the study of hydrodynamic phenomena often observed in large oceans. These phenomena include meandering currents, a persistent gyre, and transient eddies. Of particular interest is a persistent and intense anticyclonic gyre which dominates the circulation of the western Alboran Sea. A more complex time varying circulation pattern exists in the eastern Alboran. This paper reports the preliminary stages of an effort to model the circulation of the Alboran Sea. A highly idealized numerical model has simulated the major features of the upper layer circulation, particularly the anticyclonic gyre.

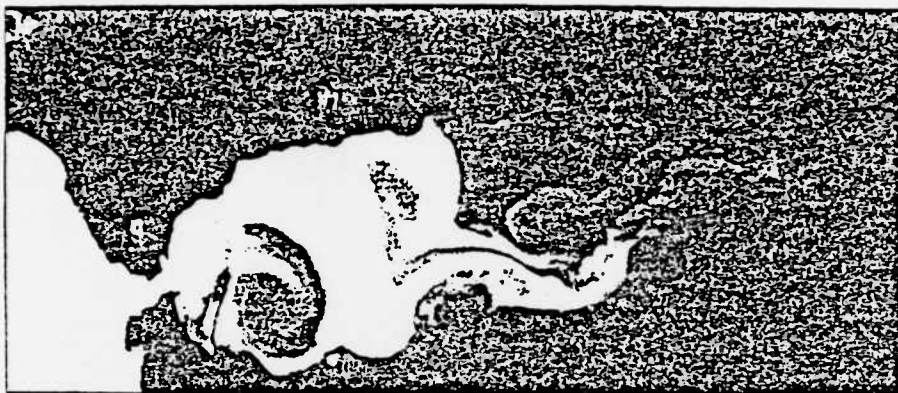
The circulation of the Alboran Sea is dependent on both Atlantic and Mediterranean waters. Atlantic water flows through the narrow (20 km wide) and shallow (300 m deep) Strait of Gibraltar into the Alboran Sea forming a 150-200 m deep surface layer. (Ovchinnikov, 1966; Lanoix, 1974; Katz, 1972). Mediterranean water enters the Alboran at its open eastern boundary and flows slowly westward in the form of an intermediate and lower layer. It has been suggested that even the deepest water can exit through the Strait (Stommel et al, 1973; Gascard, 1982). The large volume transport of inflowing Atlantic water, 1 to $2 \times 10^6 \text{ m}^3/\text{sec}$, (Lacombe, 1971; Bethoux, 1979; Lacombe, 1982) retains its identity as a narrow (30 km wide) jet with initial speeds of 100 cm/sec near the Strait (Lacombe, 1961; Peluchon and Donguy, 1962; Grousson and Faroux, 1963; Lanoix, 1974; Cheney, 1977; Petit et al, 1978; and Wannamaker, 1979). The jet enters the basin and flows northeast to approximately 4°W , curves southward and then splits (Fig. 1). Part of the jet flows to the west and is incorporated in an anticyclonic gyre, while the remainder flows southeast to Cape Tres Forcas and then along the African coast forming the southern periphery of a cyclonic circulation.

Satellite infrared imagery (Fig. 2) indicates variations in the shape, location and intensity of the persistent anticyclonic gyre which dominates the western Alboran Sea. Figure 2a shows the gyre occupying the majority of the western Alboran basin as in Fig. 1. Figure 2b shows the gyre with a smaller north-south extent and indicates a jet through the Strait of Gibraltar which flows almost due east. Hydrographic data and satellite infrared images support the year-round persistence of the gyre, although its size and location varies (Stevenson, 1977; Cheney, 1978; Wannamaker, 1979; Burkov et al, 1979; Gallagher et al, 1981). In the eastern portion of the Alboran Sea a general pattern of alternating cyclonic and anticyclonic circulations has been observed (Cheney, 1978; Lanoix, 1974). Satellite imagery shows that, compared to the western Alboran, this circulation pattern is far more variable and of smaller scale.

The purpose of this project is to simulate observed circulation patterns in the Alboran Sea and to investigate their dynamics. In this paper we report



(a)



(b)



Fig. 2. NOAA 6 infrared satellite imagery view of the Strait of Gibraltar and Alboran Sea. Lighter shades indicate colder surface temperatures. a) June 25, 1980; b) December 14, 1979.

on preliminary results from the simplest model capable of simulating major features of the circulation. This is a reduced gravity model in a semi-enclosed, rectangular domain. It is essentially a model of the first baroclinic mode and does not permit baroclinic instability or the inclusion of bottom topography.

The model formulation and parameters are discussed in Section 2. In Section 3 the model results are presented in terms of a pivotal experiment and some deviations from it. Section 3.1 discusses the pivotal experiment. The subsections which follow investigate the influences of (3.2) inflow angle, (3.3) port location, (3.4) boundary effects, and (3.5) inflow vorticity.

2. THE MODEL

A nonlinear reduced gravity model, developed for the Gulf of Mexico by Hurlburt and Thompson (1980), has been adapted for the Alboran Sea. The model equations are solved numerically using an economical semi-implicit scheme. The model consists of an active upper layer and a lower layer which is infinitely deep and at rest. It is stably stratified and has a fixed density contrast between two immiscible layers. The model assumes a hydrostatic, Boussinesq fluid in a rotating right-handed coordinate system on a β -plane. The vertically integrated model equations are

$$\begin{aligned} \frac{\partial \vec{v}_1}{\partial t} + (\nabla \cdot \vec{v}_1 + \vec{v}_1 \cdot \nabla) \vec{v}_1 + \hat{k} \times f \vec{v}_1 \\ = -g' h_1 \nabla h_1 + (\vec{\tau}_1 - \vec{\tau}_2) / \rho + A \nabla^2 \vec{v}_1 \end{aligned}$$

$$\frac{\partial h_1}{\partial t} + \nabla \cdot \vec{v}_1 = 0$$

where

$$\nabla = \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j}$$

$$\vec{v}_1 = h_1 \vec{v}_1 = h_1 (u_1 \hat{i} + v_1 \hat{j})$$

$$g' = g(\rho_2 - \rho_1) / \rho$$

$$f = f_0 + \beta(y - y_0)$$

$$\vec{\tau}_i = \tau_i^x \hat{i} + \tau_i^y \hat{j}$$

and \bar{x} and y are tangent-plane Cartesian coordinates with x directed eastward and y northward, u_1 and v_1 are the eastward and northward velocity components in the upper layer, h_1 is the upper layer thickness, t is time, g is the acceleration due to gravity, ρ_i is the density of seawater in layer i , f_0 and y_0 are the values of the Coriolis parameter and the y -coordinate at the southern boundary, $\vec{\tau}_1$ is the wind stress, and $\vec{\tau}_2$ is the interfacial stress. The remaining parameters are defined in Table 1.

TABLE 1
Model parameters for the pivotal experiment

| Parameter | Definition | Value |
|----------------------------|---|---|
| A | eddy viscosity | $250 \text{ m}^2 \text{ sec}^{-1}$ |
| β | (df/dy) | $2 \times 10^{-11} \text{ m}^{-1} \text{ sec}^{-1}$ |
| f_0 | Coriolis parameter | $8 \times 10^{-5} \text{ sec}^{-1}$ |
| g' | reduced gravity due to stratification | $.02 \text{ m sec}^{-2}$ |
| H_1 | undisturbed upper layer depth | 200 m |
| H_2 | undisturbed lower layer depth | ∞ |
| $L_x \times L_y$ | horizontal dimensions of the model domain | 600 km x 160 km |
| $\Delta x \times \Delta y$ | horizontal grid spacing for each dependent variable | 10 km x 5 km |
| Δt | time step | 1 hr. |
| \vec{v}_{lin} | inflow velocity | 100 cm/sec |
| α | angle of inflow | 21° north of east |
| t_s | inflow spin up time constant | 30 days |

Figure 1 shows the model domain superimposed on a map of the Alboran Sea. This domain is 600 km x 160 km with 10 km x 5 km grid resolution for each dependent variable. Forcing is due solely to prescribed inflow through the western port (Strait of Gibraltar). Inflow is exactly compensated by outflow through an open eastern boundary. This is accomplished by allowing normal flow at the eastern boundary to be self-determined and by imposing an integral constraint on total mass outflow (Hurlburt and Thompson, 1980). Except at the inflow and outflow ports, the boundaries are rigid and a no-slip condition is prescribed on the tangential flow. Along the eastern boundary the tangential component is set to zero one-half grid distance outside the physical domain.

The model parameters for the pivotal experiment are given in Table 1. In this experiment the western (inflow) port is centered 102 km from the southern boundary and is 15 km wide, a width appropriate for the Strait of Gibraltar

at a depth of 100 m. The specification of the model forcing is accomplished in either of two ways. 1) by prescribing velocity (\vec{v}_{lin}) or 2) by prescribing transport (\vec{V}_{lin}) and allowing the model to determine the inflow velocities. The former is used in the pivotal experiment. The total inflow transport used in the model ($2.5 \times 10^6 \text{ m}^3/\text{sec}$) is higher than observed. This value is necessary to drive a uniform inflow profile for \vec{v}_1 or \vec{V}_1 with speeds of $\sim 100 \text{ cm/sec}$, given the port width and upper layer depth in Table 1. The inflow is spun up with a time constant of 30 days to minimize the excitation of high frequency waves. The angle of inflow was varied based on direct observations (Lacombe, 1961) and on inferences from satellite imagery. The standard inflow angle was chosen to be 21° north of east based on the geometric orientation of the Strait of Gibraltar. Possibly important wind forcing (Ovchinnikov et al, 1976; Mommensen, 1978) is neglected to allow focus on the circulation driven by flow through the Strait of Gibraltar.

Substantial effort was made to assure that unphysical aspects of the model such as the grid resolution and the time step did not significantly influence the model solution. The open eastern boundary condition was a special concern and one important test of its influence is discussed in Section 3.4. The integral constraint on the total mass flux through the eastern boundary resulted in plane wave reflection of sufficient amplitude to pose a significant problem. The eddy viscosity (A) chosen for the model is the minimum value which prevents any visible oscillation in the solution due to this reflection. An eddy viscosity $2\frac{1}{2}$ times smaller yielded nearly the same solution except for some unphysical oscillations. A viscous boundary layer using a linear interfacial stress was also applied near the open eastern boundary in an effort to damp the oscillations due to the integral constraint. The maximum value for the drag coefficient was 10^{-3} sec^{-1} at the eastern boundary. It decreased exponentially away from the boundary with an e-folding width of 50 km. This aided only slightly in damping the reflection from the integral constraint. Except for the viscous boundary layer, the interfacial stress was zero.

3. MODEL RESULTS

Over 40 numerical experiments were performed for the Alboran Sea. Some preliminary results will be presented in terms of a pivotal experiment and selected variations from it. Most of the numerical solutions evolved to a steady state in about one year.

3.1 The pivotal experiment

The pivotal experiment uses the parameters in Table 1. Figure 3 shows the steady state model solution (day 500) in terms of the pycnocline anomaly (PA).

The PA is the deviation of the interface between the upper and lower layers from its initial flat position at 200 m depth. Downward deviations are positive (upper layer thicker than initially). The most striking features are 1) a meandering current which traverses the model domain from west to east, 2) a strong anticyclonic gyre in the western 240 km of the basin, and 3) a weak cyclonic circulation to the east. This pattern is very similar to the temperature field shown in a satellite image (Fig. 2a) and to Lanoix's dynamic topography (Fig. 1).

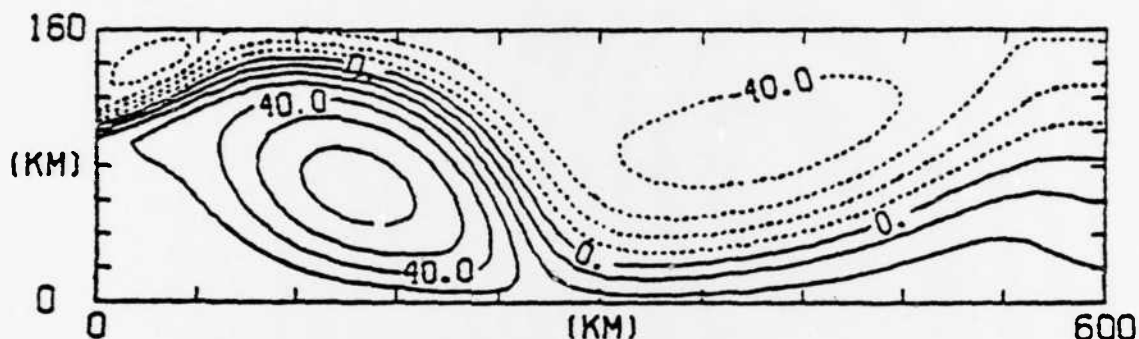


Fig. 3. PA (pynocline anomaly) of the pivotal case solution at day 500. Inflow angle is 21° north of east. Solid contours are positive (downward) deviations. Dashed contours are negative (upward) deviations. Contour interval is 10 m.

In rotating tank experiment, Whitehead and Miller (1979) attempted to simulate the Alboran Gyre using a density driven current. They suggest that the dimensions of the gyre depend on a coastline feature, Cape Tres Forcas. It has also been suggested by Porter (1976) that the dimensions of the gyre are directly related to the bottom topography with Alboran Island acting as the eastern boundary of the gyre. Yet the reduced gravity model is able to simulate an Alboran Gyre with realistic dimensions, while including neither coastline irregularities nor bottom topography. The model gyre is also a persistent rather than a transient feature of the flow, again in accord with observations noted earlier.

3.2 The effect of inflow angle

The circulation pattern in the pivotal experiment (Fig. 3) and satellite imagery (Fig. 2) suggest that the inflow angle may exert an important influence on the meandering current and the Alboran Gyre. Thus, a number of experiments were carried out varying the inflow angle. One experiment used the standard parameters from Table 1 except that the inflow entered the model domain normal to the western boundary. In the steady state solution for this case (Fig. 4), the jet enters the basin flowing due east, but quickly veers southward. The

anticyclonic gyre in the western part of the basin is restricted to a much smaller north-south extent than in the standard case. The cyclonic circulation to the east is intensified and a new anticyclonic flow appears in the eastern 200 km. This circulation pattern is similar to that of the sea surface temperature seen in the satellite infrared imagery of Fig. 2b.

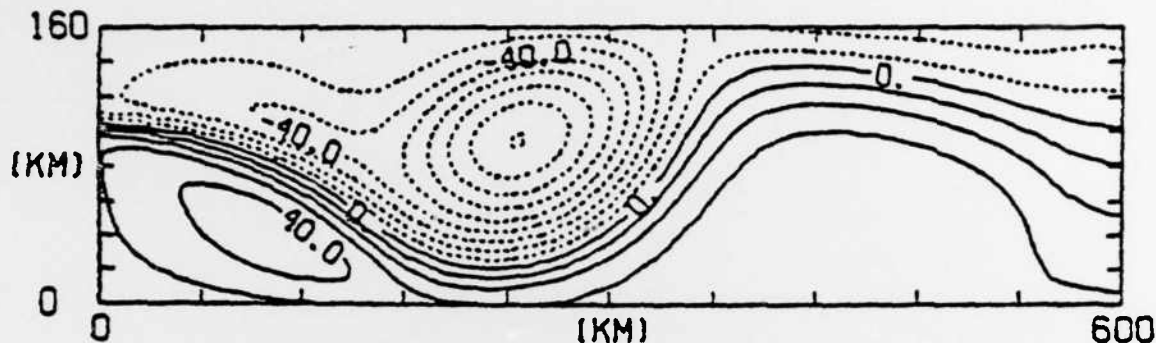


Fig. 4. PA of the pivotal case at day 500 but with due east inflow. Contour interval is 10 m.

3.3 Port location

The next set of experiments was designed to observe the importance of the north-south location of the inflow port. If the Strait of Gibraltar was located south of the basin center, how would the circulation pattern be affected? Two such experiments used the standard parameters of Table 1 except that the port was centered 7 km south of the center of the western boundary and the inflow angles were those of Fig. 3 (standard 21° north of east) and Fig. 4 (0°). The steady state solutions are presented in Fig. 5. Figure 5a, with the angled inflow of the standard case, shows 1) an anticyclonic gyre smaller than that of the standard case in the western part of the basin, 2) a strong cyclonic circulation in the central part, and 3) a weak anticyclonic circulation in the eastern part. When the inflow enters flowing due east (Fig. 5b) the western gyre is even smaller than in Fig. 5a and the two gyres to the east are slightly stronger. Clearly, the entrance of the Atlantic water in the northern half of the Alboran Sea facilitates the development of an Alboran Gyre of large north-south extent.

3.4 Boundary effects

The influence of the domain size and the open eastern boundary were also investigated. As described in Section 2, the pivotal experiment includes a viscous boundary layer near the open eastern boundary. One test compared the pivotal experiment with this boundary layer (Fig. 3) to an identical experiment without it (not shown). Except in the region of the viscous boundary layer, the results were almost identical. In the experiment without the boundary layer,

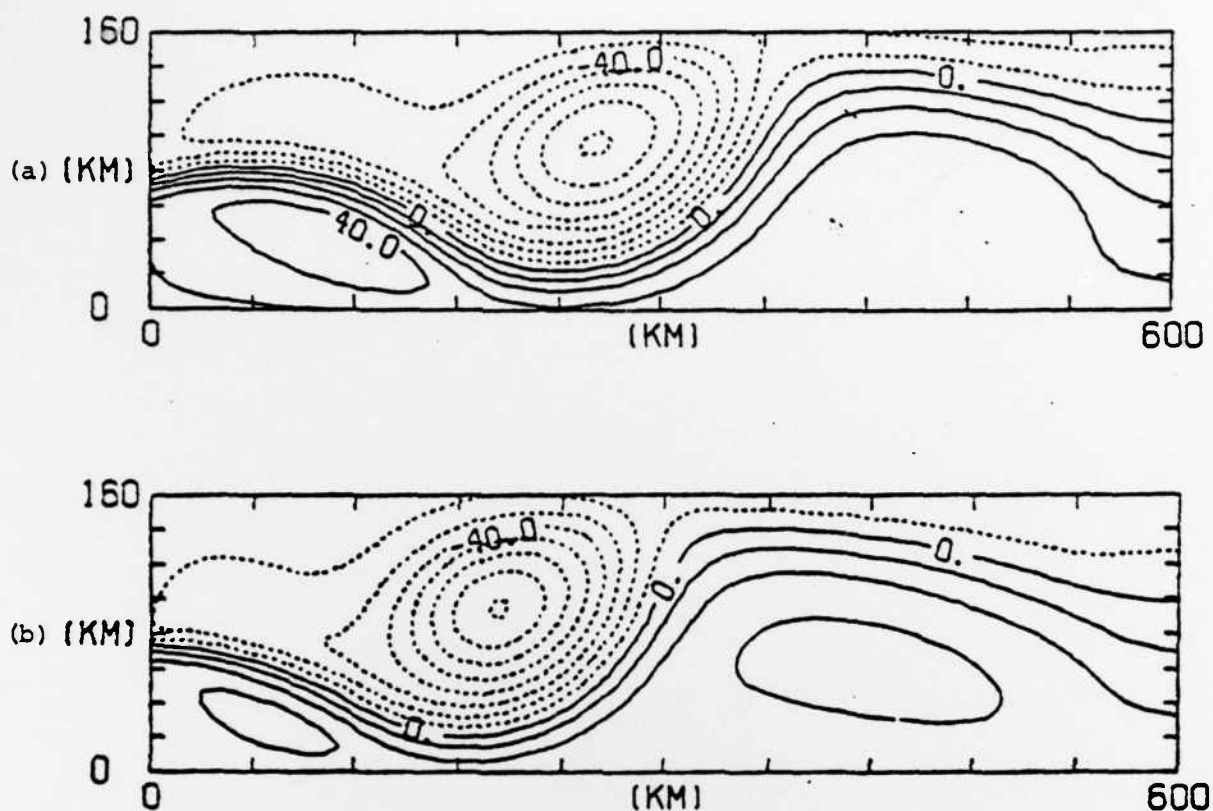


Fig. 5. PA of the pivotal case at day 500 but with the port centered 7 km south of the center of the western boundary. a) inflow angled 21° north of east; b) due east inflow. Contour interval is 10 m.

the current maintained its cross-sectional structure as it approached and passed through the open eastern boundary. When it was included, the PA contours spread out in the viscous boundary layer and the jet structure disintegrated to a more uniform flow (see Fig. 3).

Numerical experiments were also performed to determine if the open eastern boundary was seriously distorting the solution. Fig. 6 shows the results of a critical test. It compares two solutions which differ only in the east-west extent of the model domain. In each case there is a viscous boundary layer near the open eastern boundary. In this test, changing the location of the open eastern boundary caused only minor changes in the solution in the western 400 km of the model domain. The eastern 100 km in Fig. 6b differs from the same region in Fig. 6a, due mostly to the viscous boundary layer in the vicinity of the open boundary.

The effect of the north-south extent of the basin was examined by doubling the y-dimension of the standard experiment (Fig. 3) and keeping the port location slightly north of the basin center. Figure 7 shows the flow entering the basin

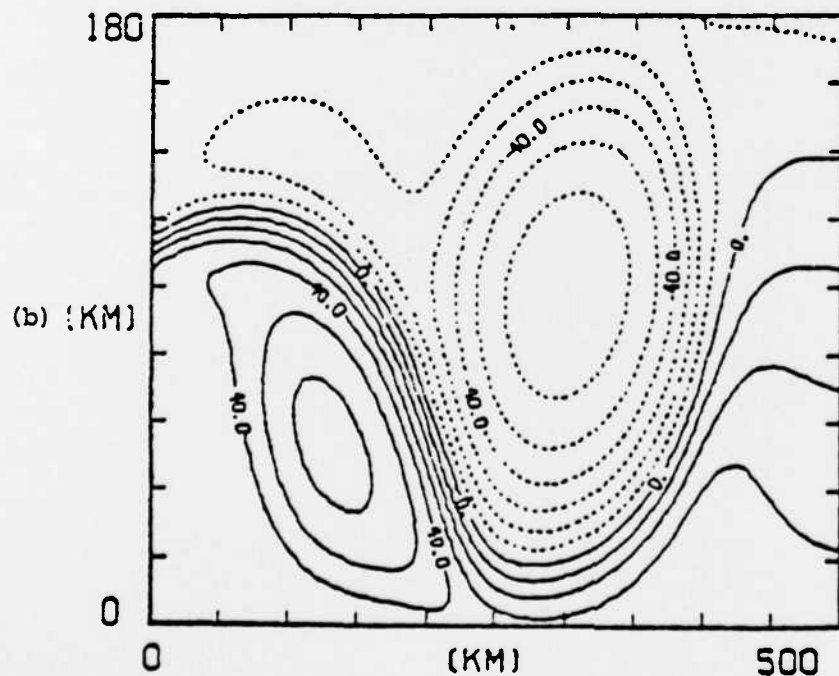
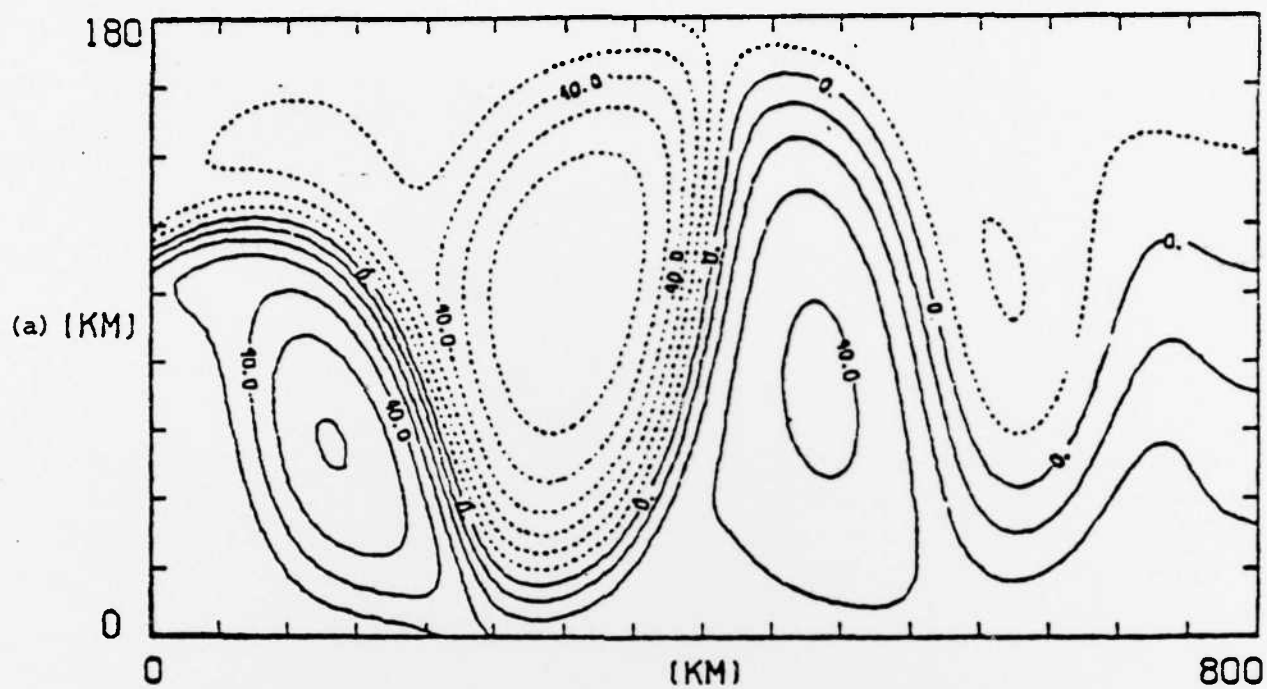


Fig. 6. PA of the pivotal case at day 190 but with different dimensions a) 180 km x 800 km basin; b) 180 km x 500 km basin. Scale factor for these figures x:y is 1:2.5. Contour interval is 10 m.

at the standard angle of 21° and then curving southward in a manner similar to Fig. 5a. Even though the north-south extent of the basin has been doubled, the northern and southern boundaries of the domain still limit the north-south scale of the current meanders. Despite a large increase in the amplitude of the meanders in Fig. 7, the wavelengths in Fig. 5a and Fig. 7 are almost the same. A striking feature in Fig. 7 is the downstream amplification of the current meanders. Less dramatic examples of this appear in some of the other figures. It should be noted that this and all the other solutions are steady and not unstable.

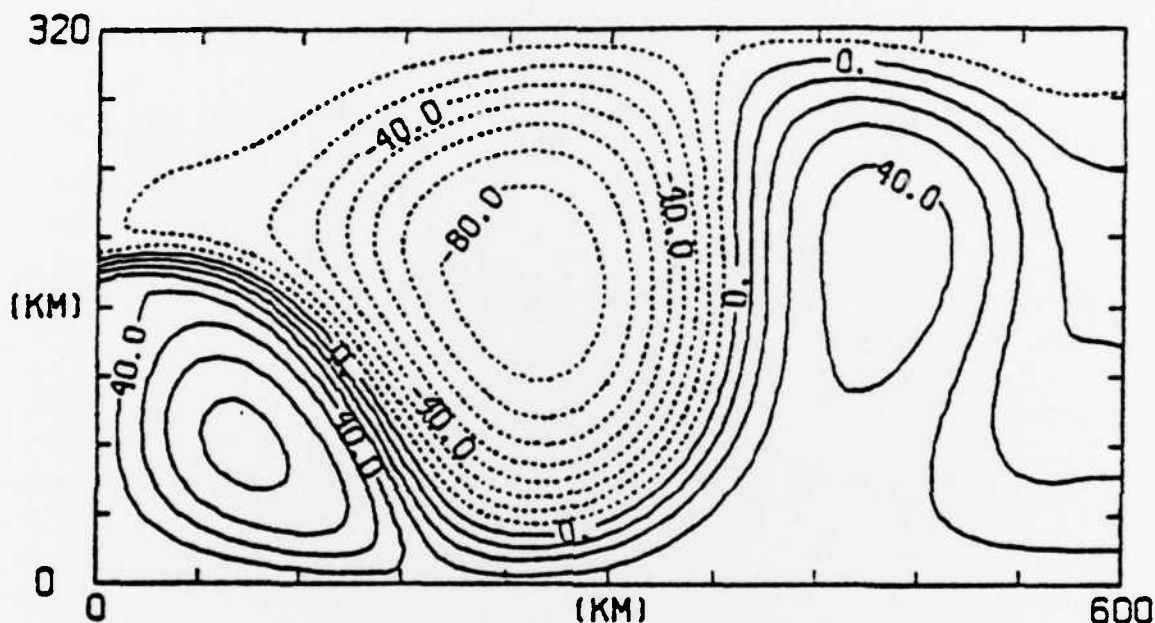


Fig. 7. PA at day 600 of an experiment where the north-south dimension of the basin has been extended to 320 km, contour interval is 10 m.

3.5 Shear at inflow

In all the experiments discussed so far, the inflow has been prescribed as a velocity profile (\vec{v}_1). However, in this model the inflow may also be prescribed in terms of transport (\vec{V}_1). In the latter case, the model partially controls the inflow velocity profile through the geostrophic tilt in the interface. Fig. 8 shows a steady state solution for an experiment similar to that shown in Fig. 5b, except that \vec{V}_1 is prescribed instead of \vec{v}_1 . In both cases the inflow is eastward. In Fig. 8 the prescribed inflow transport is $2.5 \times 10^6 \text{ m}^3/\text{sec}$. This yields inflow velocities similar to Fig. 5b, but the geostrophic tilt in the interface introduces a shear ($\partial u / \partial y$) of $1.54 \times 10^{-5} \text{ sec}^{-1}$ at inflow. Without the shear (Fig. 5b) the current turns southward after inflow, but with the shear (Fig. 8) the current turns northward. In addition, Fig. 8 shows a larger Alboran

Gyre which is further to the east and a small cyclonic gyre in the northwest corner. The possibility that vorticity at inflow turns the incoming Atlantic water northward has been suggested by Nof (1978).

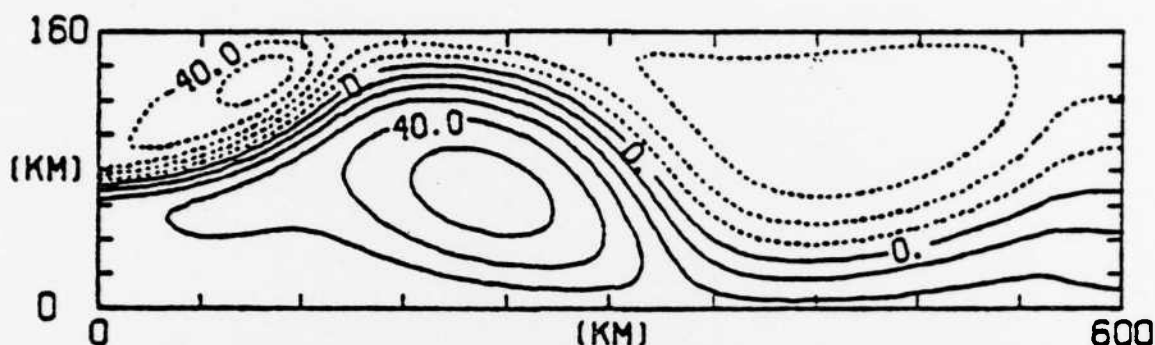


Fig. 8. PA at day 500 of a case identical to the case represented in Fig. 5b except that the model is forced with a prescribed transport. Contour interval is 10 m.

4. SUMMARY AND FUTURE WORK

A nonlinear, semi-implicit, reduced gravity numerical model (Hurlburt and Thompson, 1980) has been adapted to study the circulation in the Alboran Sea. Both hydrographic data and satellite imagery indicate the existence of a permanent anticyclonic gyre in the western Alboran. This circulation appears to be driven by a jet of Atlantic water which enters through the Strait of Gibraltar. In the model the Strait was represented by a port in the western boundary and the eastern boundary was entirely open. Model results using an idealized rectangular geometry (600 km x 160 km), no topography and a northeastward inflow through the Strait of Gibraltar show an anticyclonic gyre similar in size, shape and location to the Alboran Gyre (Fig. 3). These results closely resemble the dynamic height contours of Lanoix (Fig. 1) and suggest that topography and particular coastline features are not necessary to create a gyre with realistic dimensions and location. However, model results for the eastern Alboran show a series of cyclonic and anticyclonic circulations of much larger scale and smaller variability than observed. Additional numerical experiments showed the importance of the inflow angle and inflow vorticity in determining the size and location of the Alboran Gyre.

This paper has presented preliminary results of an attempt to model the Alboran Sea. Future work will include an investigation of the model dynamics, more realistic models, and interaction with a field experiment. The meandering current observed in the model solutions might be considered a standing Rossby wave with a highly distorted conservation of absolute vorticity trajectory (e.g. see Haltiner and Martin, 1957). The flow trajectory is strongly influenced by

the proximity of the northern and southern boundaries, the large amplitude variations in the upper layer depth, cross-isobaric inertial effects, and possibly by frictional effects. Planned model refinements include more realistic coastline geometry, an additional active layer, bottom topography, and winds. The influence of each of these features on the Alboran Gyre will be tested, but they will also be used in an attempt to obtain a more realistic simulation of the circulation in the eastern Alboran Sea. We have already begun to use the model results in the design of a NORDA (Naval Ocean Research and Development Activity) field experiment. The intended result is a cooperative interaction in which the models aid in the interpretation of the observations and the observations lead to more realistic model simulations.

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